ACHIEVING 0.02 G/BHP-HR NO_X EMISSIONS FROM A HEAVY-DUTY STOICHIOMETRIC NATURAL GAS ENGINE EQUIPPED WITH THREE-WAY CATALYST

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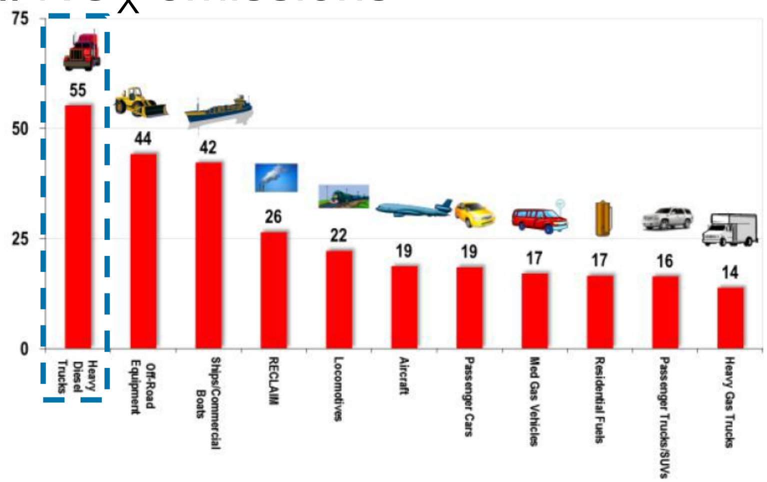
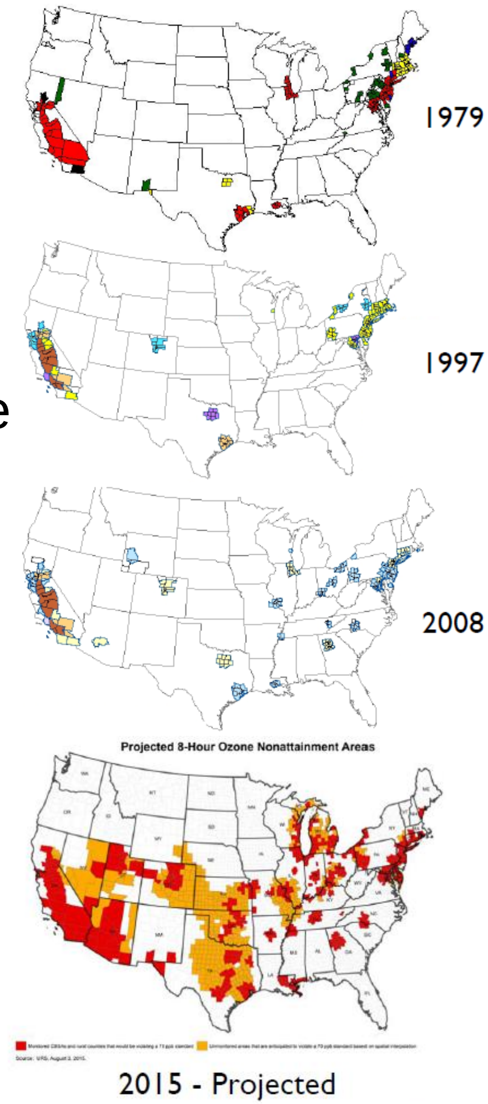
Motivation

- With the growth in population across the United States ozone nonattainment areas continue to grow
  - Continued tightening of ozone standard
- 2015 EPA rulemaking changed NAAQS for ozone to 70 ppb
- CARB Inventory shows on-road heavy-duty trucks are ~20% of all NO_X emissions



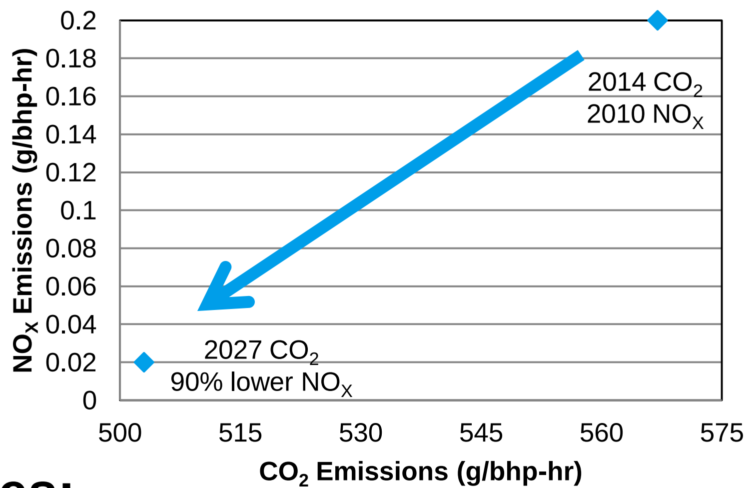
- The 0.20 g/bhp-hr NO_X standard still isn't enough…



NO_X Emission Goals: Reduction and Efficiency

Two main goals:

- Achieve 0.02 g/bhp-hr NO_X emissions over the U.S. Heavy-Duty FTP, RMC-SET and the European WHTC
- Minimize the impact to GHG emissions
  - Provide the pathway towards meeting Phase 2 GHG standards



Secondary objectives:

- Observe the emissions over the CARB extended idle test as well as 3 low-load vocational cycles

Test Engine

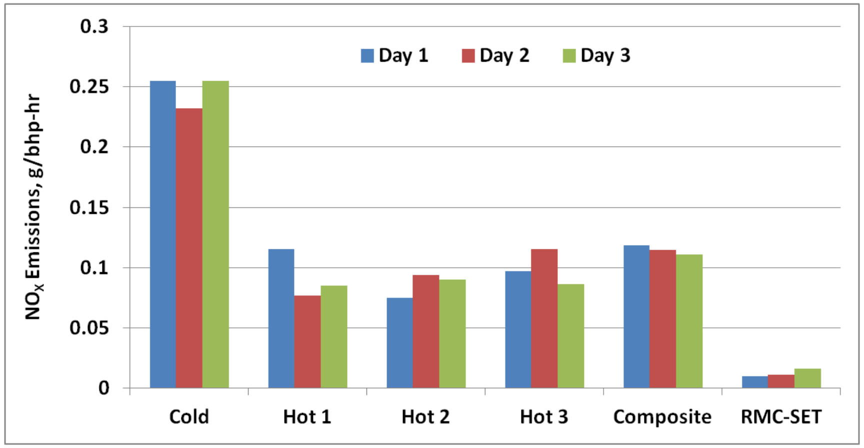
2014 model year Cummins ISX12-G engine certified to 2010 U.S. Heavy-Duty emissions standards

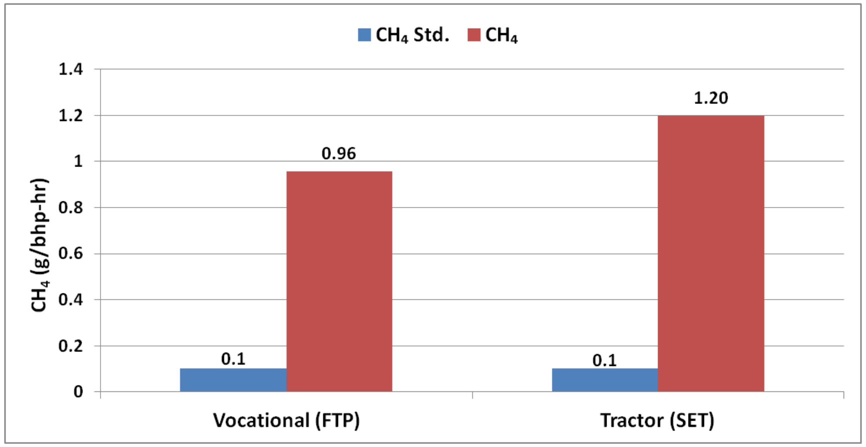
- 238 kW @ 1800 RPM // 1559 Nm @ 1200 RPM
- High-pressure loop, cooled EGR
- Stoichiometric – single-point, upstream fueling
- Three-way catalyst
- Bus application

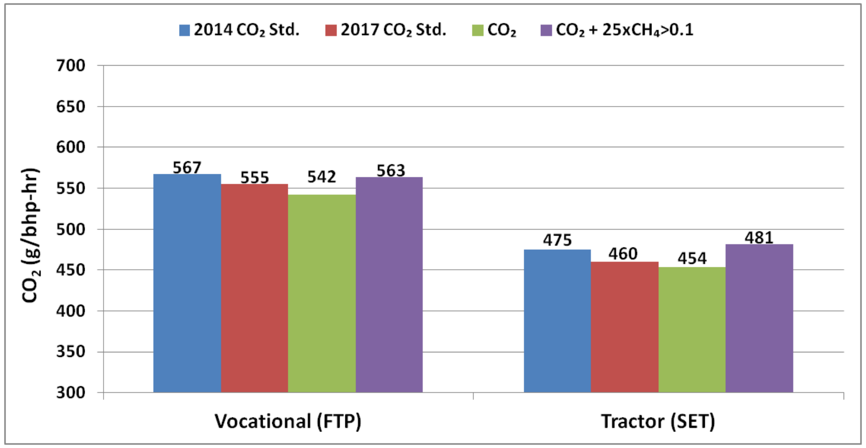
Baseline Emissions

The engine was tested over various cycles to examine emissions and find improvement areas

- Certification cycles
  - US Heavy-Duty FTP
  - US Heavy-Duty RMC-SET

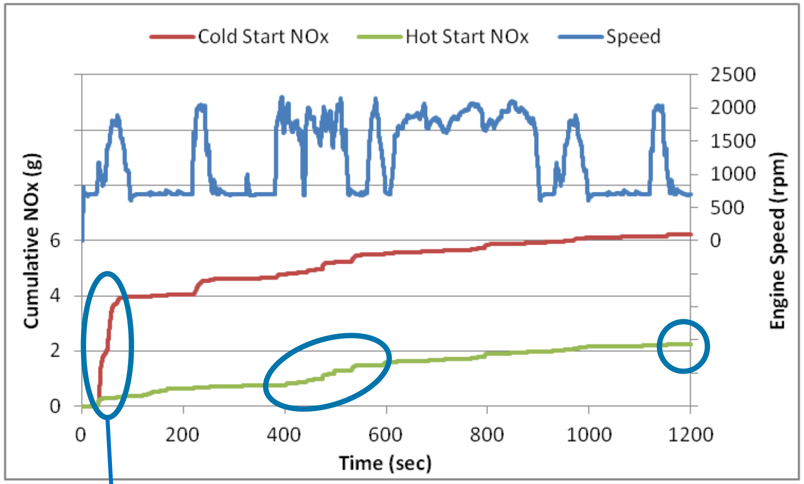


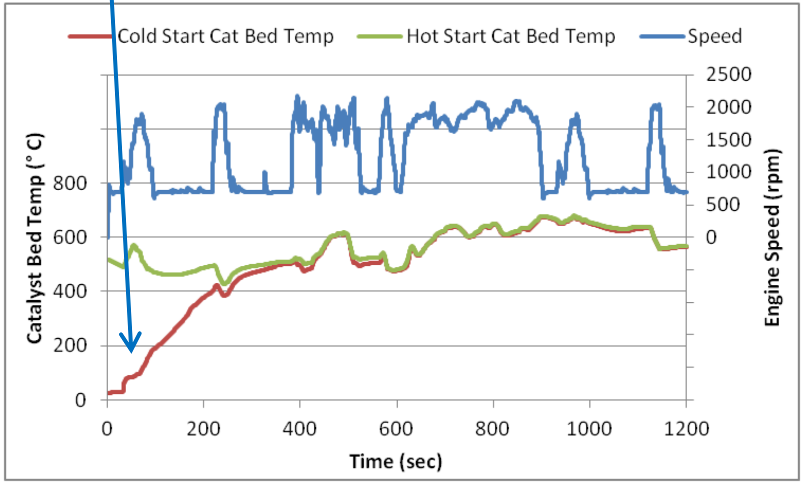




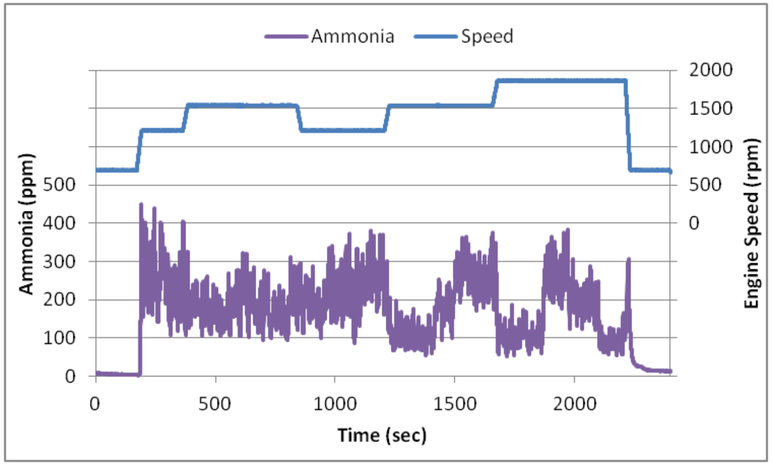
Baseline Emissions: Certification Cycles

Looking at the emissions gives insight into areas of improvement





- Cold-start NO_X emissions
  - Catalyst light-off
  - Open-loop fueling
- Hot-start NO_X emissions
  - AFR control
- RMC-SET
  - NH_3 emissions
  - Slightly rich AFR set-point



Engine Hardware Improvements

The baseline engine was upgraded with new hardware and engine control unit/calibration to achieve the 0.02 g/bhp-hr NO_X emission target

Baseline Engine	Low NO_X Demonstration Engine
Single Underfloor TWC (22.4 L)	Close-coupled TWC (9 L) & Underfloor TWC (20 L)
Stock CM2180A ECM	Aftermarket EControls ECU
No CCV System	Full CCV System

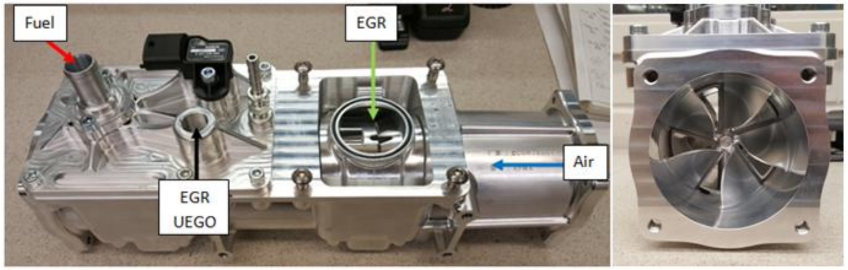
- Lower PM and gaseous emissions
- Lower oil consumption

	ISLG FTP NO_X Blowby Emissions (g/bhp-hr)
Cold Start	0.044
Hot Start	0.008
Composite	0.013

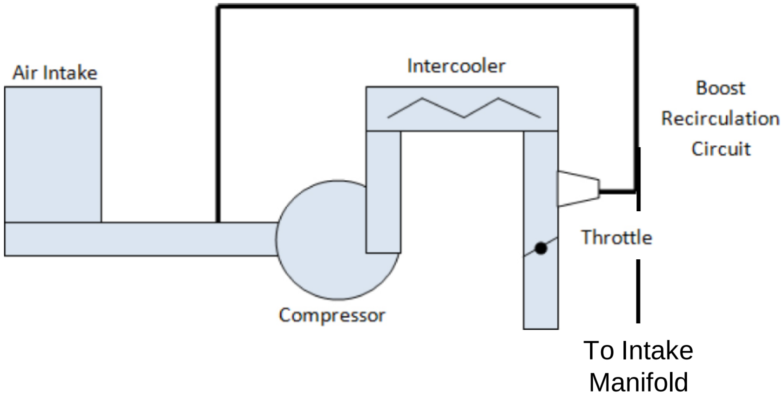
Engine Hardware Improvements

Additional hardware was added to increase the EGR tolerance and transient performance of the engine

- EGR Tolerance
  - Baseline: Capacitive discharge ignition coil system
  - Demonstration: Improved fuel-air-EGR mixer and higher energy DC ignition coil system



- Additional Improvements
  - Continuous flow valve (CFV) for fueling
  - Electronically controlled wastegate
  - Boost recirculation valve



Closed Loop Fueling

Large focus on keeping the engine within closed loop fueling

Baseline Engine

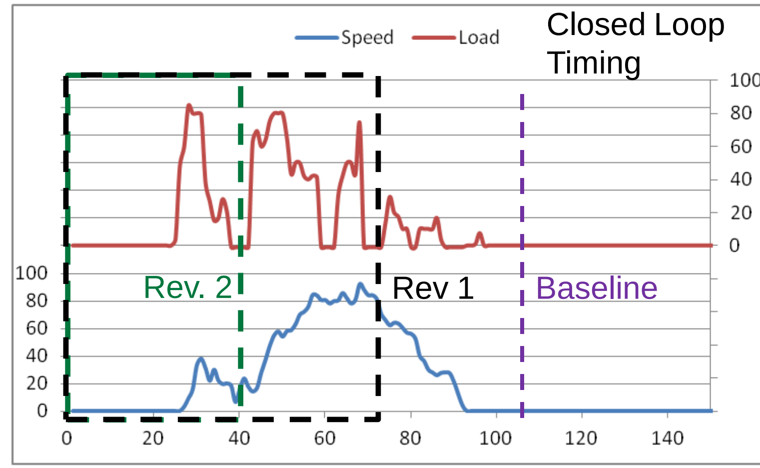
Switching O_2 sensor

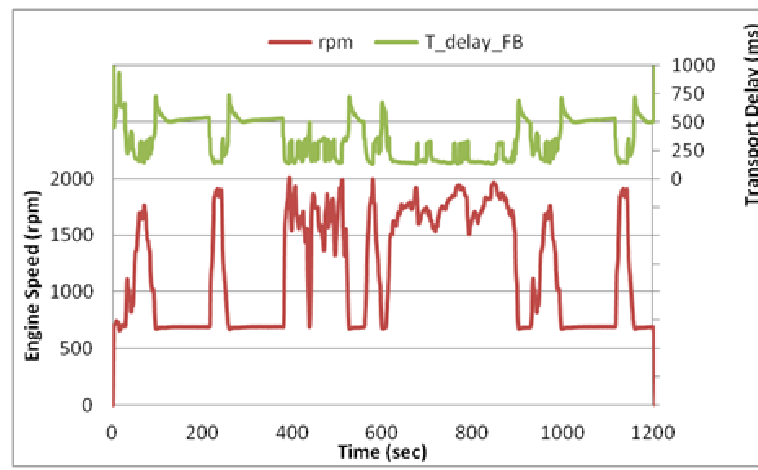
UEGO Sensor

- Pre- & post-catalyst switching O_2 sensors

- UEGO sensor located just downstream of turbocharger

Low NO_X Demonstration Engine

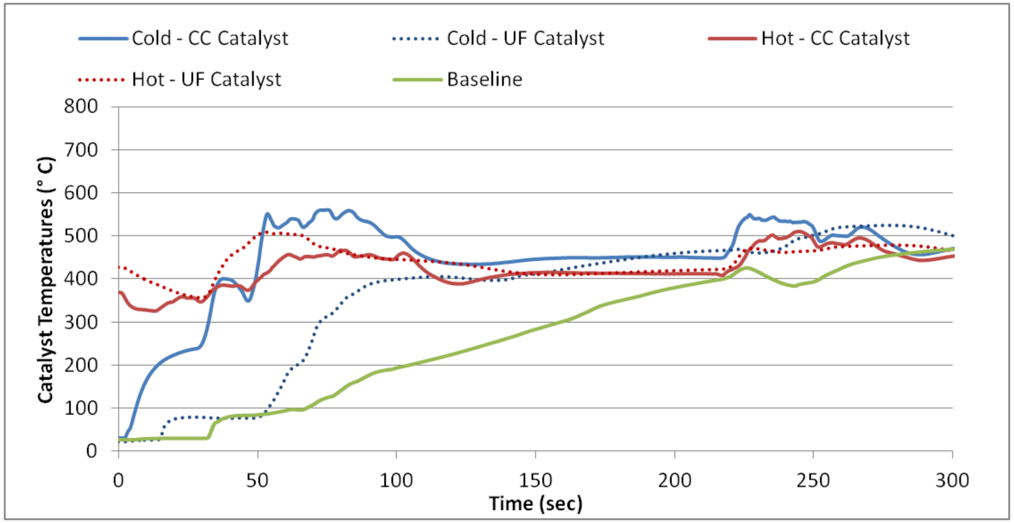




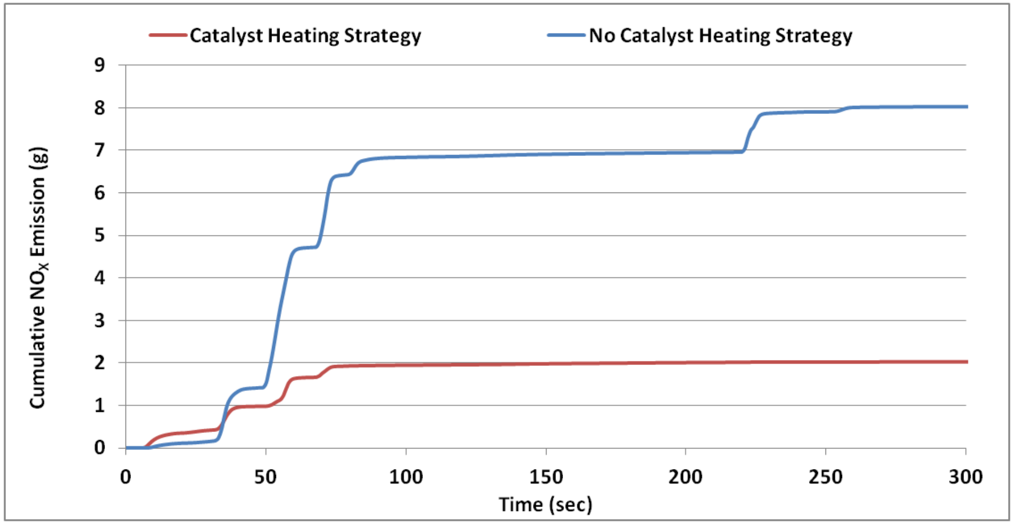
- Transport and feedback delay minimized
- Accurate measurements of fuel supply, intake and exhaust volume required

Cold Start Improvements

- Catalyst heating strategy
  - Ignition timing after TDC
  - Slight enrichment
  - EGR use disabled for first 30 seconds

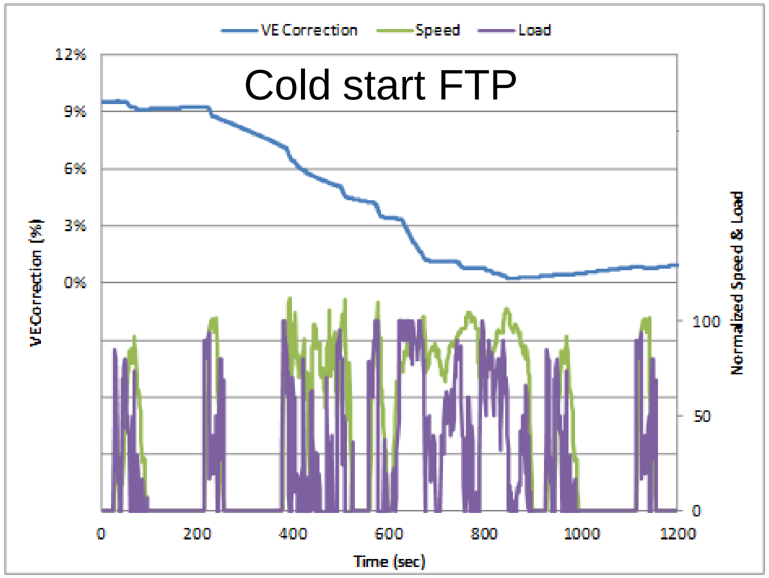


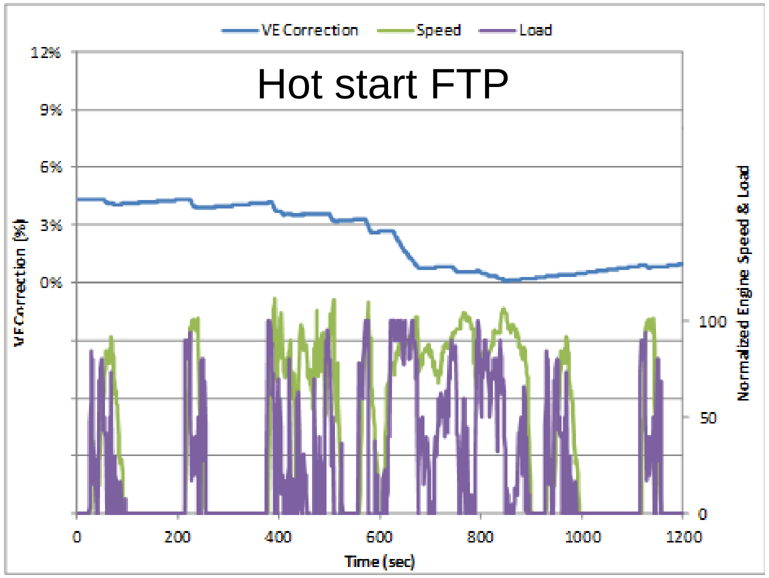
- Emissions difference
  - 4x increase in NO_X emissions without catalyst heating
  - Increase in cycle work without catalyst heating results in 3.4x increase in $BSNO_X$



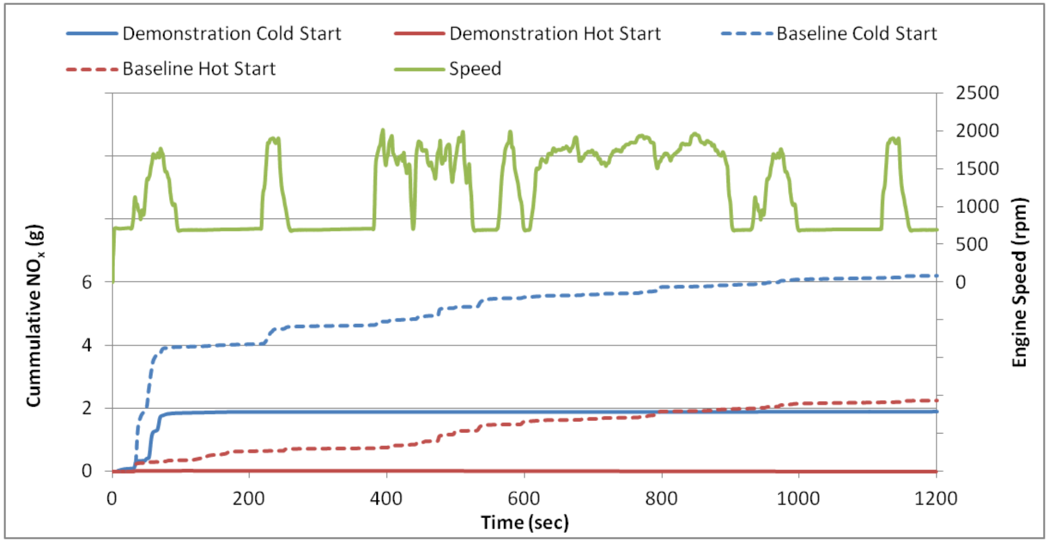
Engine Calibration Improvements

- Long time constant volumetric efficiency (VE) correction
  - Used to correct for cylinder wall temperature:
    - Engine speed & load history
    - Coolant temperature
  - ECU's adaptive table learns hot operation
    - Cold operation has incorrect adjustments and takes too long to update
  - Allows for larger VE correction when engine is cold



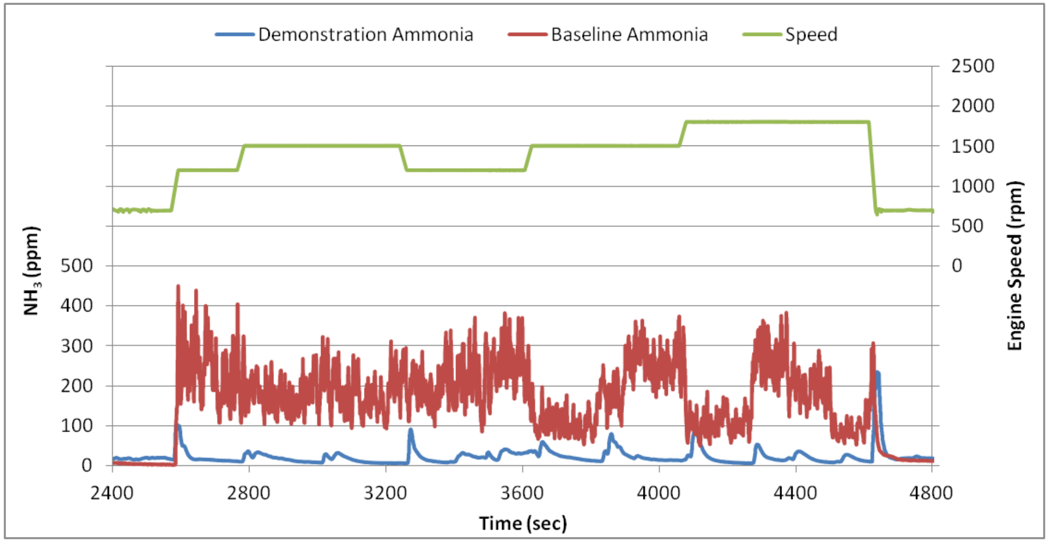


Improved Calibration & Hardware Results: FTP & RMC-SET



- Demonstration cold start emissions equivalent to baseline hot start

- Near zero NO_X emissions over the RMC-SET
- Significantly lower NH_3 emissions



CARB Demonstration

Testing performed over the span of a couple weeks

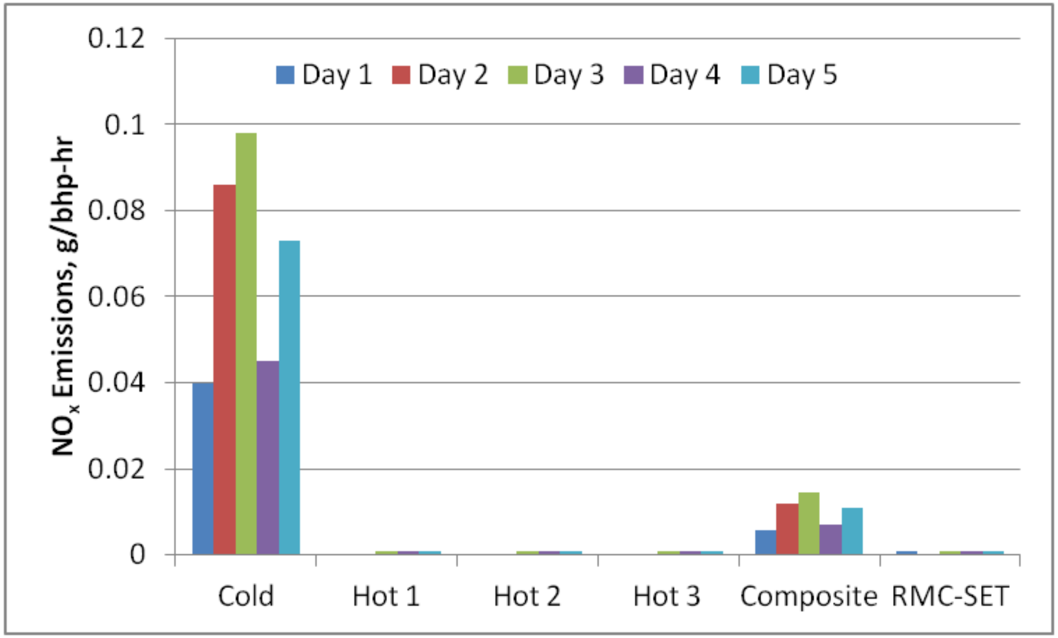
- US certification cycles
  - 5 repeats of cold + 3 hot FTP & RMC-SET
- Non-US certification cycles
  - 3 repeats of cold + 3 hot WHTCs & CARB extended idle
- Low load vocational
  - 3 repeats of NYBC, OCTA, and Cruise-Creep

- Testing performed in compliance with 40 CFR 1065
- Raw and dilute emissions measurements to verify low emissions levels
  - Both raw and dilute measurements required two different gas calibration ranges for cold and hot start
    - Ex. 250 ppm NO_X range for cold-start and 25 ppm NO_X range for hot-start (dilute)

NO_X Emissions: FTP, RMC-SET & WHTC

Certification cycles were the primary focus for calibration efforts

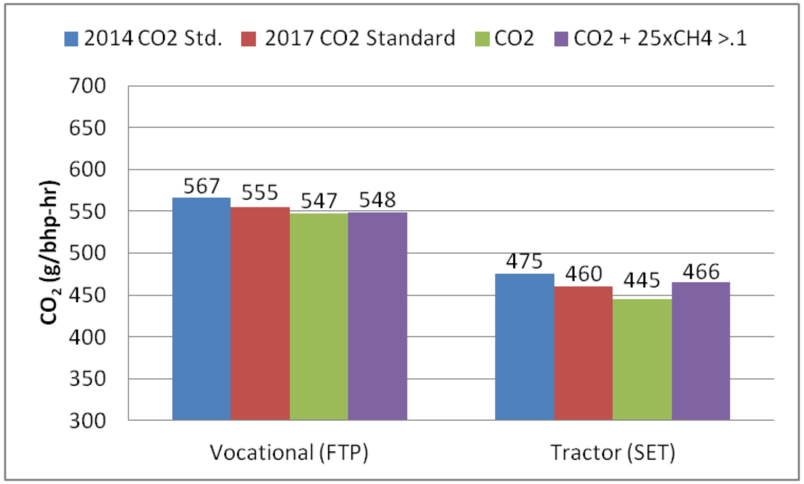
	NO_X Emissions Comparison, g/bhp-hr						
	FTP			RMC-SET	WHTC		
	Cold	Hot	Composite		Cold	Hot	Composite
Baseline	0.247	0.093	0.115	0.012	0.310	0.308	0.308
Low NO_X Engine	0.065	0.001	0.010	0.001	0.043	0.006	0.011
Reduction	**74%**	**99%**	**91%**	**92%**	**86%**	**98%**	**96%**

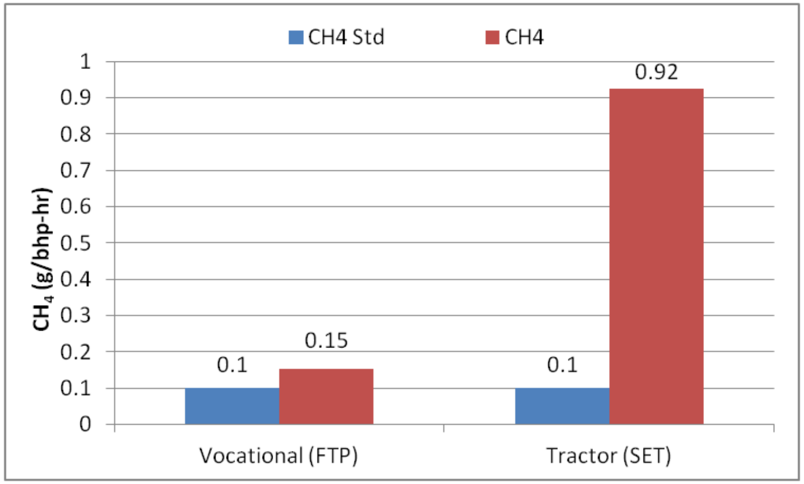


Other Emissions: FTP, RMC-SET & WHTC

GHG emissions and ammonia were of interest

	Other Emissions Comparison			
	Pollutant	FTP	RMC-SET	WHTC
Baseline	CH_4, g/bhp-hr	0.96	1.20	1.54
	NH_3, avg. ppm	76	162	100
	CO_2, g/bhp-hr	542	454	510
Low NO_X Engine	CH_4, g/bhp-hr	0.15	0.92	0.10
	NH_3, avg. ppm	52	37	44
	CO_2, g/bhp-hr	547	445	513
Reduction	CH_4, g/bhp-hr	84%	23%	94%
	NH_3, avg. ppm	32%	77%	56%
	CO_2, g/bhp-hr	-0.9%	2.0%	-0.6%



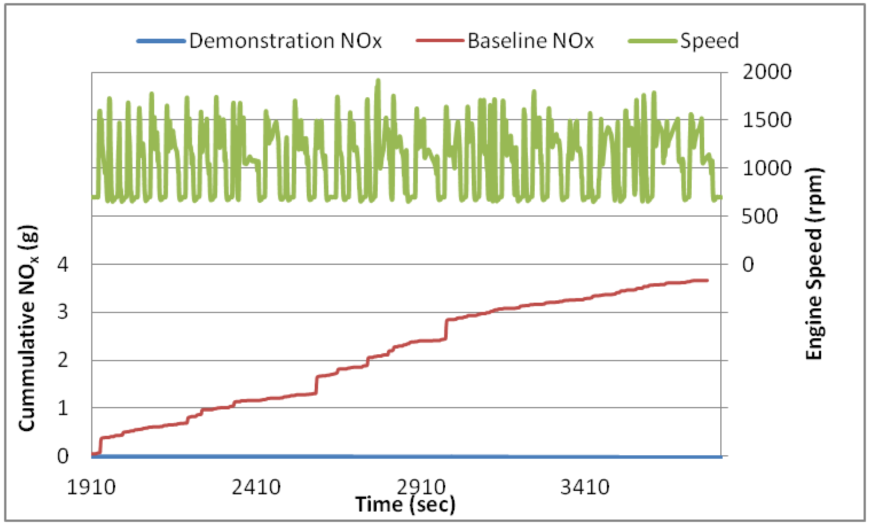


Low Load Vocational Cycles

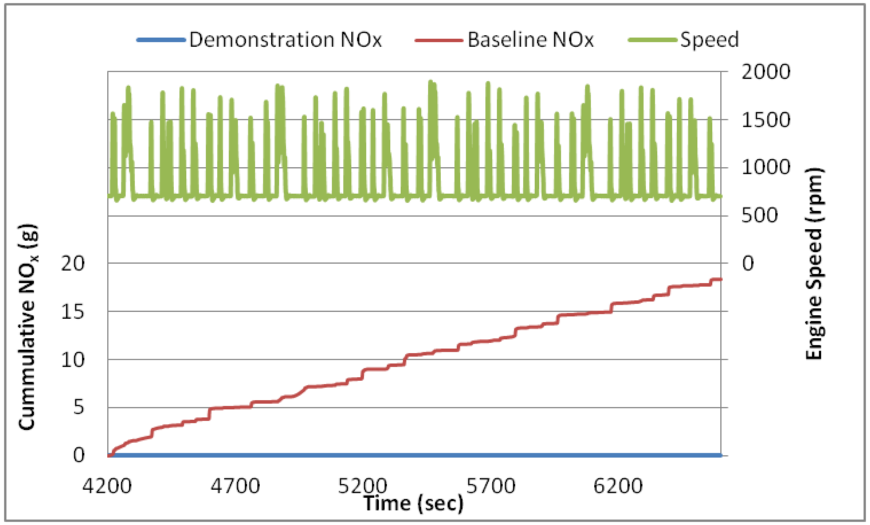
Near zero NO_X emissions with no GHG/fuel penalty over low load cycles

	OCTA Tailpipe Emissions, g/bhp-hr			NYBC Tailpipe Emissions, g/bhp-hr		
	NO_X	CO_2	CH_4	NO_X	CO_2	CH_4
Baseline	0.112	552.8	1.078	0.907	672.4	1.893
Low NO_X Engine	0.000	552.3	0.039	0.002	667.1	0.421
Reduction	**99.7%**	**0%**	**96%**	**99.8%**	**1%**	**78%**

OCTA



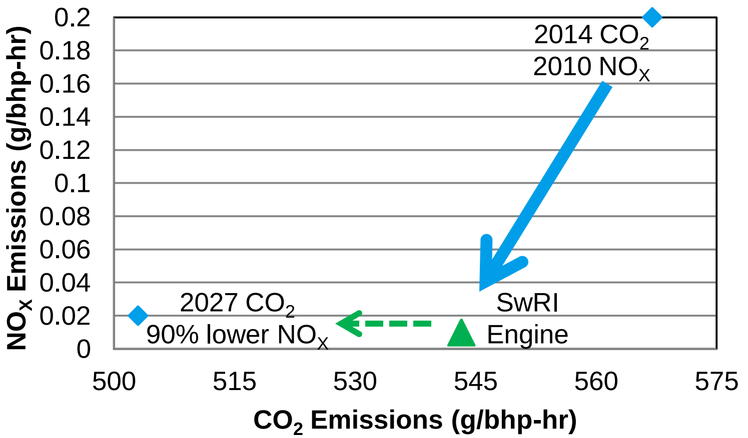
NYBC



Conclusions

This engine and calibration met the 0.02 g/bhp-hr NO_X emission target

- Required:
  - Close-coupled and underfloor TWC
  - Rapid catalyst heating strategy
  - Improved AFR control
  - Improved EGR tolerance
    - New hardware



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Future Work

- Fuel penalty associated with rapid catalyst light-off will need to be addressed
  - Southwest Research Institute has already conducted internal research; results to be released soon

- Further reductions require improved AFR control
  - Oxygen storage model would reduce emissions further
  - NH_3 levels were higher than the 10 ppm target
  - CH_4 emissions above the 0.1 g/bhp-hr cap for Phase 1 and Phase 2 GHG Standards
    - RMC-SET with high space velocities may require CH_4 oxidation catalyst

- Small excursions from stoichiometric can result in large NO_X breakthroughs
  - HD-OBD requirements will apply to CNG engines starting 2018 and robust AFR monitoring will be important in ensuring low NO_X emissions in the future

Acknowledgements

James Chiu

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Air Resources Board

EControls

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Questions